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Final Report to the Office of Naval Research
Interpretation of seafloor characteristics
in the western Arabian Sea

Stephen A. Swift
David A. Ross
Dept. of Geology and Geophysics MS#24
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

Swift: ph: 508-289-2626 fax: 508-457-2150 email: sswift@whoi.edu
Ross: ph: 508-289-2578 fax: 508-457-2187 email: dross@whoi.edu

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ABSTRACT

The objective of this study was to provide a regional geologic interpretation of seafloor geotechnical composition, shallow subbottom stratigraphy, and geomorphology of the western Arabian Sea. Too few samples of the seafloor have been taken in this area to map the region from direct measurement. To provide regional coverage we used data from bathymetry, GLORIA side-scan, and echo sounding lines to supplement core samples obtained by academic institutions and NAVOCEANO. Much of the western Arabian sea basin is covered with pelagic-to-hemipelagic sediments to depths of >2-3 m. The exceptions are (1) the shelves and the current-swept shoal area near Socotra Island where carbonate sand and hardgrounds are more common; (2) canyons and gullies on the continental slope where slumping exposes over-consolidated deposits and contributes coarse, poorly-sorted debris to the canyon axes; (3) ridge crest regions; and (4) lobes of massive sands at the mouths of distributary channels on the Indus Fan.

LONG TERM GOALS

Interpretation of geotechnical properties and geomorphologic characteristics of the seafloor and near-subsurface sediments requires the integration of paleoenvironmental, tectonic, geologic data and associated processes. Geotechnical and geomorphologic interpretations are often limited to small areal studies and qualitative observations. Our long-term goal is to apply an integrated approach to provide the Navy with realistic seafloor geotechnical maps of shallow littoral and adjacent deep-water environments in the northwest Indian Ocean and the adjacent marginal seas.

OBJECTIVE

The objective of this study was to provide a regional geologic interpretation of seafloor geotechnical composition, shallow subbottom stratigraphy and geomorphology of the western Arabian Sea. This study examined the composition and configuration of the present day seafloor and near-subsurface sediments and the mechanisms or processes that produced these results. The nature and distribution of seafloor microtopography and geotechnical properties were of interest. The effects of basin evolution and changes in sea level were also included to specifically address anomalous geologic conditions or geohazards. We integrated temporal oceanographic and meteorological processes that may affect or change surface sediment cover.

APPROACH

Too few samples of the seafloor have been taken in this area to map the region from direct measurement. To provide regional coverage we used data from ETOPO5 and multibeam bathymetry, interpretive maps from a GLORIA side-scan survey, and echo sounding lines to supplement core samples obtained by academic institutions and NAVOCEANO. In areas of uncertainty, we inferred seafloor conditions by generalizing the results of detailed sedimentological work in small areas to wider areas of the basin.

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WORK COMPLETED

The primary product of our research is a map of the western Arabian Sea showing the distribution of seafloor provinces having similar lithologic and acoustic properties or assemblages of properties. The provinces were mapped on the basis of four types of information. (1) We used lithologies of sediment cores extracted from unpublished reports obtained from LDEO, WHOI, NGDC, and NAVOCEANO. The core locations, core numbers, and sediment types are indicated on the map. (2) We digitized the location of backscatter targets mapped by Kenyon et al. (1995) using the GLORIA side-scan mapping system (6.5 kHz). (3) We were guided by interpretations of 3.5 kHz echosounding profiles mapped by Kolla and Coumes (1987). (4) We used interpretations of seafloor sedimentary processes and core studies published by Kolla and Coumes (1987), Cramp et al. (1990), and Prins et al. (2000). We were unable to locate publications that reported direct measurements of geotechnical properties at the seafloor or on recovered sediment samples. Table 1 summarizes our interpretation of the properties of the seafloor provinces.

Geotechnical properties in the middle and lower fan were difficult to interpret because the seafloor is comprised of layers of variable thickness. Measurements made on sediment cores are done on individual layers whereas reflectivity observations by vertical (eg. echosounders) and side-scan sonars integrates the properties in the upper 0.5-10 m depending on the frequency and power of the sonar and the scattering and attenuation properties of the seafloor. In regions of the middle and lower Indus fan that are outside the axes of distributary channels, the upper 1-10 m of sediment is carbonate-rich foraminiferal ooze with up to 25% aeolian and hemipelagic clay. The lower Indus fan is distinguished from the middle Indus fan by having a thinner surficial layer of soft sediment. Sand and silt layers occur below this layer. Using the available data, no inherent difference between the two provinces can be distinguished in the properties of the constituent layers. In Table 1 we report core measurements on both types of material.

RESULTS

1. Shelf sediments

Shelf sediments are principally comprised of biogenic carbonate and terrigenous-derived mineral sands. The relative proportions depend on the proximity of coastal scarps and rivers. Patches of mud also occur and are most common along river-dominated shelves like that off the Indus River Delta. The shoal regions between the island of Socotra and the northeast tip of Somalia are unusual. Cores from the region indicate both mud and hardground (bent core barrels). It is likely that surface currents passing through the wide channels sweep the seafloor, pond fine-grained carbonate mud in local depressions, and scour elevated regions leaving sand, gravel, and chemically-cemented rock. The data set available is inadequate to map the distribution of properties at the map scale used. Table 1 gives a range of properties expected in the shelf region based on measurements made elsewhere.

2. Slope sediments

Core descriptions and published reports indicate that the deep basin of the Arabian Sea is covered with a layer of calcareous foraminifera-bearing silty-clay or clayey-silt that is Holocene in age and uncompacted. In most regions this layer of soft surficial sediment is at least 35 cm thick. This description applies to the marginal slopes of the basin with the exception of active canyons. Since sea level reached its present position ~6,000 years ago, the Indus River delta has not yet prograded across the continental shelf to the head of the Indus Canyon, so transport of material on this slope is greatly diminished (von Rad and Tahir, 1997; Prins et al., 2000). Nevertheless, terrigenous sand is found on the floor of the canyon and in upper fan channels. Other canyons along this portion of the India-Pakistani margin appear to be inactive and are likely floored with hemipelagic mud and small slump deposits. Along the southern coast of Oman, it is likely that there is significant seasonal sediment transport to the shelf by run-off from rain brought by the southwest monsoon. There are small slope canyons offshore, and we expect that the floors and slopes of these features include coarse-grained terrigenous debris. We have included in

this province the tectonically elevated basement highs along the Alula-Fartek fracture zone at 51°E and the Owens fracture zone. Coring and seismic studies in both regions indicates a combination of pelagic sedimentation and slump-exposed, semi-lithified carbonate sediment (Thiede, 1976; Mountain and Prell, 1989). Fault scarps are prominent and steep.

3. Spreading ridges

A spreading center extends from the center line of the Gulf of Aden (Aden Rift) into the Arabian Sea along the Sheba Ridge and connects to the Carlsberg Ridge along the Owen fracture zone (Figure 1). We mapped the axis of the rift based on ETOPO2 bathymetry, earthquake locations and magnetic anomaly patterns reported by Stein and Cochran (1985) and Fournier et al. (2001). There is little public information available on the nature of the seafloor along this feature. The NGDC inventory of seafloor samples indicates that the ridge has been dredged, so the axis includes exposures of volcanic rock. We have also heard that a French-Japanese survey of the Sheba Ridge in 2000 mapped hydrothermal vents. It is likely then that the seafloor for ~20 km on either side of the ridge crest includes sheet lava flows, small volcanoes, and steep fault scarps. All of these features may be covered with patches of pelagic ooze that increase in thickness off axis. A reasonable analog for the spreading centers in the western Arabian Sea may be found in the seafloor reflectivity and the spatial density and inter-relationships of tectonic features described by Dauteuil et al (2001), who interpreted multibeam data in the western Gulf of Aden.

4. Pelagic sediments

As indicated above, the seafloor throughout the deep basin is covered by a soft, carbonate-rich mud (lutite, ooze, marl) deposited by typical deep ocean pelagic processes. The composition and minor variations of uppermost sediment layer are described more fully in Kolla et al. (1981), Shankar et al. (1987), Sirocko et al. (2000), and Prins et al. (2000). This unit continues from the continental slope onto the abyssal plains and up onto the flanks of the spreading center ridges. In general, pelagic ooze buries sandy-silty turbidite layers derived from the continental shelf and slope that were deposited during the last glacial maximum 15,000-20,000 years ago. In regions mapped as pelagic sediments, we expect the thickness of pelagic ooze puts the turbidites deeper than the reach of side-scan sonar systems. Descriptions of cores recovered from the northern end of the Somali Basin report sand-size foraminifera shells as a minor constituent and no evidence of derived turbidite layers derived from the shelf. We map pelagic sediments around the northern (proximal) end of the Indus Fan and onto the Laxmi Ridge located near 68°E, 16°N. Here, this thick unit has hemipelagic character that overlies turbidites deposited during the last low sea level stand.

Indus Fan provinces

We map three provinces on the Indus Fan. These provinces are discriminated on the basis of the depth of burial to thickened units of terrigenous silt and sand deposited during the last glacial maximum and the early rise in sea level. Although we mark distinct boundaries on our map, separations are poorly defined and are likely to be gradational over tens of kilometers. The boundary towards the north with pelagic sediment province is indistinct and arbitrary.

The Indus fan is comprised of overlapping channel-levee systems deposited by distributary channel networks that extended over 1000 km from the mouth of the slope canyon to the distal end of the fan (Kenyon et al., 1995). The width of these systems reaches only about 200 km. Once abandoned, little turbidite activity occurs within the channels and the seafloor is covered with pelagic sediments. Prins et al. (2000) dated the last lateral switch to ~ 25,000 years ago. They found that termination of turbidite activity in the most recent system occurred at ~11,500 years ago, when post-glacial sea level rise first began to flood the continental shelf.

5. Middle fan

Sediment cores indicate that the top of turbidite deposits is at least 3 m depth below seafloor. This region is closest to the shelf and therefore has higher rates of hemipelagic sedimentation than the lower fan. It has also been inactive the longest. Numerous

channels cross this region (Kolla and Coumes, 1987), but these features have been inactive for long periods of time and are covered with pelagic drape.

6. Lower fan

Sediment cores indicate that terrigenous sand and silt layers often occur within 1-2 m of the seafloor. This province is characterized by meandering distributary channels with less than 1 m of pelagic drape, which have been identified using Gloria side-scan reflectivity maps (Kenyon et al., 1995; Cramp et al., 1990) and echosounding profiles (Kolla and Coumes, 1987). At least two channel-levee systems have been identified in the region (Kenyon et al., 1995).

7. Channel-mouth sand lobe

Kenyon et al. (1995) report a relatively flat region with no acoustic penetration that lies seaward of the most recently active channel system. The seafloor is generally flat although apparent channels with relief less than 4 m have been identified. Coring was unsuccessful here and the seafloor is comprised of massive sands with 30 cm or less of hemipelagic ooze (Cramp et al., 1990). We extended the unit seaward to the edge of the fan based on echosounding results.

IMPACT/APPLICATIONS

Much of the western Arabian sea basin is covered with pelagic-to-hemipelagic sediments to depths of >2-3 m. The exceptions are (1) the shelves and the current-swept shoal area near Socotra Island where carbonate sand and hardgrounds are more common; (2) canyons and gullies on the continental slope where slumping exposes over-consolidated deposits and contributes coarse, poorly-sorted debris to the canyon axes; and (3) ridge crest regions ~40 km wide in which lava is exposed at the seafloor (or thinly buried) and tectonic faulting forms steep-sided cliffs that contribute slumped debris to the central valley floor. The region east of the Owens and Carlsburg ridges is covered with deposits from the Indus river. On the fan, hemipelagic to pelagic layers cover the upper fan and much of the continental slope. The middle and lower fan is comprised of over-lapping, elongate channel systems (1000 km by 200 km) that begin at the mouth of the slope canyon. Coarse deposits in old channels are buried deeper than 3 m by soft-pelagic sediments. In the most recent two systems, the axes of distributary channels contain coarse-grained deposits covered by 1-2 m of soft sediment. These channels terminate seaward in a channel-mouth lobe comprised of massive sands.

TRANSITIONS

Multibeam files, gridded bathymetry, and a map of seafloor geotechnical provinces have been transferred to the Naval Oceanographic Office (Code N92, Peggy Schexnayder, point-of-contact).

RELATED PRODUCTS

Identified above.

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Table 1. Geotechnical properties of seafloor sediment in the western Arabian Sea.

Sediment type	Thickness (m)	Density (gm/cc)		P velocity (m/s)		S velocity (m/s)
		mean	range	mean	range	mean
<u>Shelf</u>						
Calcareous sand	1-30	1.64 ¹	1.61-1.67	1581 ²	1617-1649	81 ³
Calcareous clayey silt	1-40	1.85 ⁴	1.77-1.92	1584 ⁴	1565-1603	122 ⁵
<u>Continental slope and rise</u>						
Calcareous clayey silt	5-10	1.82 ⁶	1.78-1.86 ⁶	1485 ⁷	1476-1494 ⁷	114 ⁵
<u>Pelagic sediments</u>						
Calcareous mud	2-20	1.45 ¹	1.38-1.55	1470 ²	1450-1480	75 ³
<u>Middle fan</u>						
Calcareous mud	3-8	1.45 ¹	1.38-1.55	1470 ²	1450-1480	75 ³
Terrigenous silt	0.1-10	1.85 ⁴	1.77-1.92	1584 ⁴	1565-1603	122 ⁵
<u>Lower fan</u>						
Calcareous mud	1-2	1.45 ¹	1.38-1.55	1470 ²	1450-1480	75 ³
Terrigenous silt	0.1-10	1.85 ⁴	1.77-1.92	1584 ⁴	1565-1603	122 ⁵
<u>Sandy lobe</u>						
Terrigenous sand	1-30	2.01 ⁸	1.61-1.67	1798 ⁸	1565-1597	197 ⁸

¹ Hartmann et al. (1971) Table 12, computed average water content of 39% for 13 samples with 50-90% > 63 μ . Used $\rho_{\text{water}} = 1.029$ gm/cc and $\rho_{\text{solid}} = 2.71$ gm/cc to compute ρ_{bulk} .

² Hamilton and Bachman (1982) p. 1902, regression equation between V_p and ρ_{bulk} for continental terraces (their Fig. 8). Compare to 1557-1568 m/s (in situ) and 1580-1604 m/s (lab) for an Adriatic sand (Barbagelata et al., 1991) and 1587 m/s (lab) for grain supported carbonates in the Bahamas (Lavoie and Anderson, 1991).

³ Barbagelata et al. (1991) p. 312, Table 1, in situ V_p/V_s ratio of 19.5. Hamilton (1980) p. 1326, fig. 16, regression equation gives unrealistically high values.

⁴ From averages computed using data sent by J. Meinert measured on surface sediment cores taken in 1991 in a detailed study area (28°30'-29°30'N, 49°30'-50°30'E). I averaged all values of density and V_p in the upper 20 cm ($n = 3-10$). I sorted the cores into "clayey silt" and "silty clay" based on where the core locations plotted with respect to the line in Hartmann et al., 1971, fig. 21, separating the 10-50% and 1-10% > 63 μ fields. I then averaged the surface 20 cm values for all cores that were from each of the two fields: "clayey silt", 10-50%, number of cores = 9; "silty clay", 1-10%, number = 7. Ranges are the 95% confidence limits for the means.

⁵ Hamilton (1979) Table I, p. 1094, 0 m depth, $V_p/V_s = 13$.

⁶ Average of four density measurements made by Navoceano on Silas Bent cruise 260593 core 3 for samples described as clayey silt and silt located at 8-9 cm and at 49-107 cm core depth. I assume here that composition has less affect on density than texture and that I can substitute the results of analyses on terrigenous material for analyses on calcareous material. I make this assumption because I have no density measurements for the cores taken on Wilkes cruises in regions mapped as calcareous clayey silt.

⁷I averaged velocity measurements made by Navoceano on three cores taken on Wilkes 343802 (8-2, 8-2, and 8-12). For these three averages, I used only values in the top 25 cm and then one value every 25 cm down the length of the core. I then averaged the mean values for the three cores. The range is one standard deviation of the mean.

⁸Hamilton et al. (1970). Used data for shallow water sand at the Tower.